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DETERMINING HF MIRROR REFLECTANCES WITH THE CAVITY  
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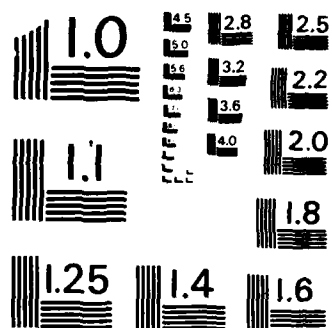
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## Determining HF Mirror Reflectances with the Cavity Phase-Shift Method

M. A. KWOK and R. H. UEUNTEN  
Aerophysics Laboratory  
Laboratory Operations  
The Aerospace Corporation  
El Segundo, CA 90245

30 June 1986

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Prepared for  
SPACE DIVISION  
AIR FORCE SYSTEMS COMMAND  
Los Angeles Air Force Station  
P.O. Box 92960, Worldway Postal Center  
Los Angeles, CA 90009-2960

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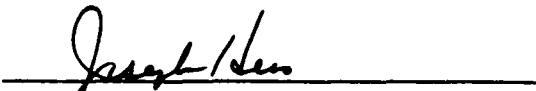
This report was submitted by The Aerospace Corporation, El Segundo, CA 90245 under Contract No. F04701-85-C-0086 with the Space Division, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by W. P. Thompson, Jr., Director, Aerophysics Laboratory.

Lt Scott Levinson/YNS was the project officer for Mission-Oriented Investigation and Experimentation (MOIE) Program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

  
SCOTT LEVINSON, Lt, USAF  
MOIE Project Officer  
SD/YNS

  
JOSEPH HESS, GM-15  
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SD-TR-86-37	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DETERMINING HF MIRROR REFLECTANCES WITH THE CAVITY PHASE-SHIFT METHOD		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER TR-0086(6930-01)-10
7. AUTHOR(s) Munson A. Kwok and Robert H. Ueunten		8. CONTRACT OR GRANT NUMBER(s) F04701-85-C-0086
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space Division Los Angeles Air Force Station Los Angeles, Calif. 90009-2960		12. REPORT DATE 30 June 1986
		13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Laser applications Midinfrared optics Optical component metrology Reflectance measurement		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Current work with the cavity phase shift (CAPS) method concentrates on HF laser wavelengths between 2.6 and 3.0 $\mu\text{m}$ . This method and continued advancements in experimental techniques are described. With use of a cavity dither the accuracy of reflectance measurements has been improved over previous work to $\pm 0.0004$ for reflectances around 0.995. Results of measurements on dielectric-coated elements are reported, as are studies on metallic monolayers placed on nontransmitting substrates. The required CAPS configuration in these cases is a three-mirror arrangement		

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

That permits angle-of-incidence variation. In this mode the CAPS method becomes a technique for verifying the quality of optical coatings on particular resonator designs. *Remarks - 1/21/5*

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# PREFACE

Helpful discussions have been provided by R. A. Chodsko, R. Dyer, R. R. Giedt, J. M. Herbelin, and H. Mirels. This work was supported in part by the Defense Advanced Research Projects Agency and conducted under U.S. Air Force Space Division (AFSD) Contract F04701-83-C-0084. The review of this material does not imply the Department of Defense's endorsement of factual accuracy or its opinion.



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## I. INTRODUCTION

The cavity phase-shift (CAPS) method for determining high reflectances has now been demonstrated at infrared wavelengths using cw HF laser line emissions as the coherent sources.<sup>1</sup> In particular, work has been performed at a wavelength of 2.911  $\mu\text{m}$ , the HF  $P_2 \rightarrow 1(8)$  line. Previously the method had been successfully applied at shorter wavelengths in the visible and near-infrared.<sup>2,3</sup>

As a step toward the study of more generalized mirror configurations, the current paper describes the improved accuracy of the method at HF wavelengths and the use of the three-mirror version of the method for mirrors with non-transmitting substrates.

## II. EXPERIMENT

The CAPS method consists of making a mirror with unknown high reflectance part of a high-Q interferometric optical cavity structure. As a result of a large number of multiple passes by radiation off the unknown reflectance, high sensitivity and great accuracy in measuring the unknown reflectance can be achieved.

The radiation source is an intensity-modulated laser beam that is passed through the interferometric structure by transverse mode matching. A phase shift in the sine wave modulation of intensity yields a direct measurement of the unknown reflectance. The phase shift is determined by means of a phase-sensitive lock-in amplifier that detects the difference between a reference phase without cavity and then the phase, including lagging shift, with cavity. Because the method detects phase changes in the modulated intensity and not intensity changes, the phase-check mirror system of four simple flat mirrors does not require crucial adjustment as it is flipped into and out of the cavity axis (Fig. 1).

In the three-mirror cavity version of the method, as shown in Fig. 1, the cavity is defined as beginning from the hatched flat mirror with reflectance  $R_1$ , through the intracavity mirror of unknown reflectance  $R$ , to the hatched spherically curved mirror with reflectance  $R_2$ . Both mirrors  $R_1$  and  $R_2$  require transmitting substrates, but it is obvious that the unknown  $R$  does not. In this configuration the unknown reflectance is related to the measured phase shift  $\theta$  by

$$\tan \theta = \frac{4\pi f L}{c} \frac{R_1(1 - 2A)R^2R_2}{1 - R_1(1 - 2A)R^2R_2}$$

where  $f$  is the intensity-modulation frequency;  $L$  is the interferometer length;  $c$  is the speed of light within the cavity; and  $A$  is the single-pass, very weak atmospheric absorbance from  $R_1$  to  $R_2$ . The product  $R_1R_2$  can be determined

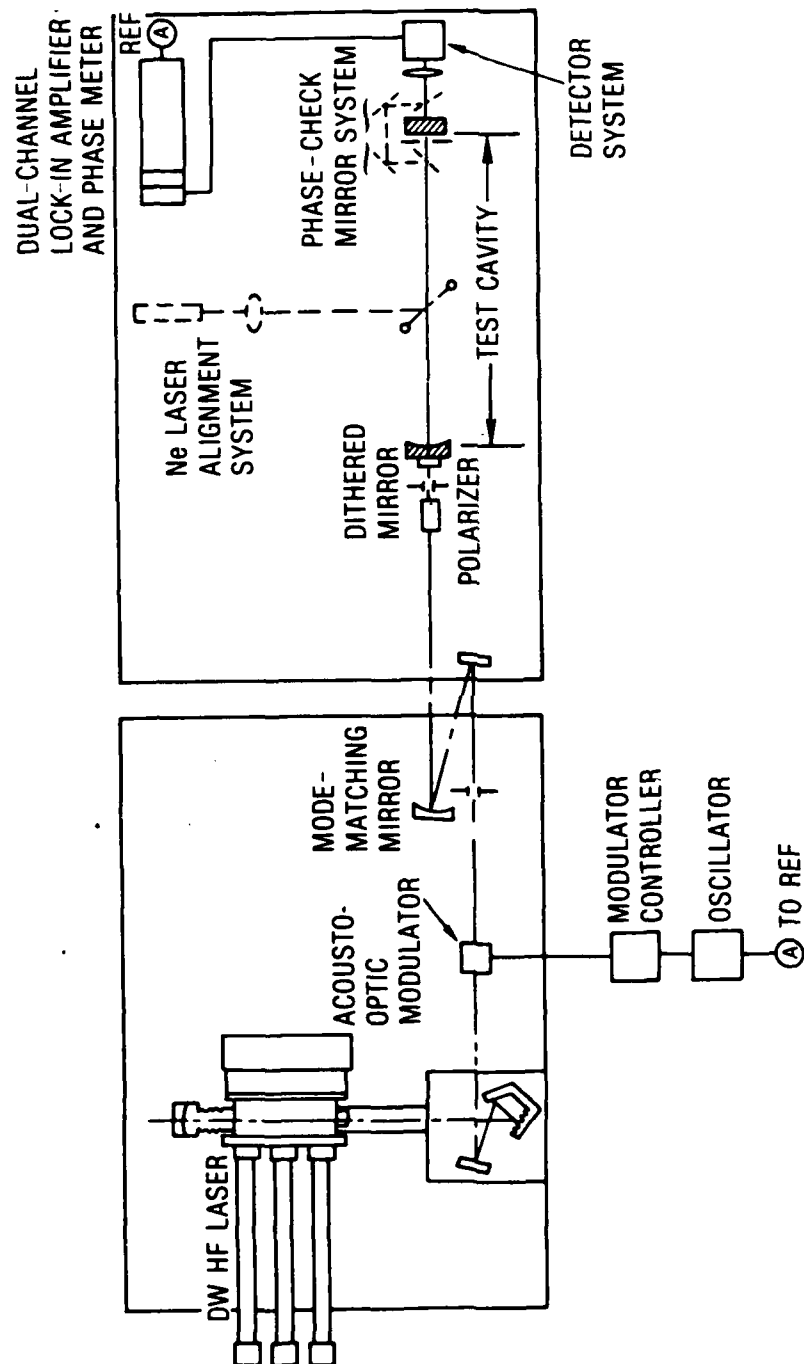


Fig. 1. Schematic of Cavity Phase-Shift Method at HF Laser Wavelengths

absolutely in a prior measurement by using the two-mirror configuration previously described.<sup>1</sup> Then the formula is identical to that above with R taken as unity. Hence the three-mirror configuration yields an absolute measurement for reflectance R. The transmitting mirrors are dielectric-layer-coated on silicon substrates with antireflection coatings on the polished flat backs, also previously described.

In this work, generally  $R_1$  will be flat and  $R_2$  will be spherically curved at a 200-cm radius of curvature. In the midinfrared region, absorptions can occur as a result of water vapor and, to a lesser extent, trace impurities in the air. This consideration can be totally eliminated in this measurement by means of a flush box filled with dry  $N_2$ . For minimally affected lines such as  $P_2(8)$  we have chosen, for convenience's sake, to make an atmospheric water-vapor absorption correction that uses a technique devised by J. Bernard<sup>4</sup> on the basis of HF laser transmission data provided by D. J. Spencer.<sup>5</sup> This approach requires the day-to-day monitoring of the relative humidity and room temperature to determine the water density. Then

$$A = P_{\lambda} N_{H_2O} L$$

where  $P_{\lambda}$  is the absorption coefficient at 294 K (in  $\text{cm}^{-1} \text{atm}^{-1}$ ) observed by Spencer,  $N_{H_2O}$  is the water density in appropriate units, and L is the cavity length. Generally,  $P_{\lambda}$  is insensitive to slight changes in room temperature, but  $N_{H_2O}$  is not. For HF  $P_2(8)$ ,  $P_{\lambda} = 4.133 \times 10^{-4}$ . Quantity A is usually  $0(10^{-4})$ ; therefore, this correction affects slightly the size of the uncertainties  $[0(10^{-4})]$  in the reflectance measurement.

In these studies, a particular improvement to be investigated is the use of the cavity dither to improve the number of possible longitudinal modes that could be excited in the test cavity. Hence the observed signal stability could improve, as well as lock in, the signal-to-noise ratio. This dither, the well-known version with three piezoelectric stacks (Burleigh PZ-90), provides a maximum 6- $\mu\text{m}$  variation in L.

The detector signal-to-noise ratio can also be improved by making the round-trip length of the test cavity longer than the coherence length of the active laser cavity. Consequently, the time-varying coherence effects involving consecutive multiple passes would be minimized at the mirrors. In the current work, the effective coherence length of the HF laser is around 2 m for the ~ 50% grating coupler. The data for the three-mirror configuration at a 4-m round-trip distance have consequently been observed to be better behaved with a smaller range of scatter than data taken with the shorter two-mirror configuration.

The degree of polarization of the laser radiation has been estimated at various stations by means of an analyzer consisting of six zinc selenide Brewster-angle plates. The degree of linear polarization of the radiation has been found to be better than  $5 \times 10^{-3}$ , the limit of measurement at the laser; it is 0.02 after the radiation passes through beam-shaping optics and the three-mirror CAPS cavity. Relative to the test cavity, the linearly polarized radiation has been kept in s-polarization for all these tests.

An intracavity iris has been placed so as to provide an estimate of the mode coverage within the test cavity, and to verify optimized mode matching. The remainder of the experiment and instrumentation are as previously discussed.<sup>1</sup>

### III. RESULTS

With the dither in place, it was immediately observed that a significant improvement in accuracy, as reflected in the uncertainty or scatter of the phase-angle measurement, could be achieved. The uncertainty in the angle was reduced by over a factor of five, down to typically  $\pm 1$  to  $2^\circ$  on all measurements. This improvement in accuracy was assisted by using the lock-in amplifier (PAR 5202) solely as a phase meter. For this amplifier the stated instrumental accuracy on relative phase changes can be as fine as  $0.2^\circ$  under the best circumstances. Therefore, some room for improvement remains. The improved signal stability on lock-in time scales of 10 msec to 10 sec provided an opportunity for finer alignments that further improved the Q of the cavity. As the functional variation of the phase meter voltage output was sufficiently well-behaved during tuning through the minima or maxima of angles, some future semi-automation by digital control, using phase meter voltage as part of a feedback loop, might be considered. Certainly, the experiment is now amenable to the data-recording and processing techniques available via microcomputer devices.

Once the maximum phase-angle condition is reached with the two-mirror test cavity, an absolute measurement for  $R_1 R_2$  can be made with the specially cleaned<sup>2</sup> silicon mirrors, as shown in Fig. 2. For data taken over three days, the measured  $\tan\theta$  is plotted as a function of intensity-modulation frequency  $f$ , which ranges from 150 through 600 KHz.

The distribution of points about the straight line for a given test series and that for day-to-day studies seems about the same. That is, the accuracy and precision are similar. The results for two different days are given as circles and triangles. The curved line at the abscissa suggests the computed range of positive deviation in  $\tan\theta$  for a  $+2.0^\circ$  uncertainty in angle  $\theta$ . The observed data lie within a phase-angle uncertainty of  $\pm 2^\circ$ .

The straight-line, least-squares-fit yields a slope measurement that is then related to  $R_1 R_2$  by

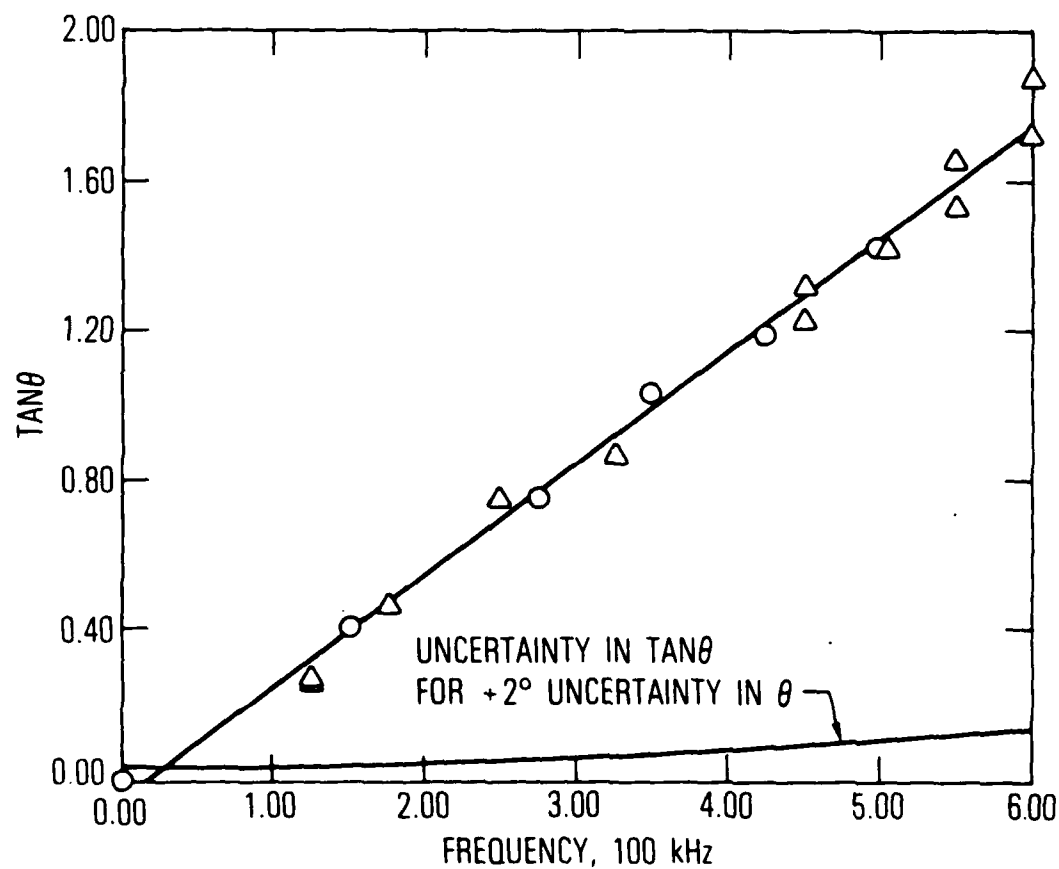


Fig. 2. Two-Mirror Test Cavity for Determining  $R_1R_2$ . Mirrors are dielectric-coated silicon substrates, one flat, one with 200-cm R.D.C. Plot of  $\tan\theta$  vs. intensity of modulation frequency.  $L = 89.0$  cm, HF  $P_2(8)$ ,  $2.911\text{-}\mu\text{m}$  wavelength. Test area: 4 mm diameter at mirror centers.  $R_1R_2 = 0.9892$ .

$$S = \frac{4\pi L}{c} \frac{R_1 R_2 (1 - 2A)}{1 - R_1 R_2 (1 - 2A)}$$

In this case we find  $R_1 R_2 = 0.9892 \pm 0.0009$ . If both coatings are assumed to be identical,  $R_1 = R_2$  and  $R_1 = R_2 = 0.9946 \pm 0.0004$  for the dielectric coatings. In the previous work<sup>1</sup> we had reported a reflectance of  $0.9920 \pm 0.0050$  for uncleaned coatings. The combination of careful cleaning and improved techniques has raised the deduced reflectance and significantly reduced the uncertainty in the measurement. This observation is consistent with the fact that the CAPS method yields a lower-bound (i.e., less than or equal to) reflectance result. Equality is achieved when the optics are properly prepared and the experiment is properly performed in all its details. The product  $R_1 R_2$  is observed to be stable over several days.

With the product  $R_1 R_2$  established, a three-mirror CAPS configuration was constructed with the intracavity mirror consisting of a dielectric-coated flat on a transmitting silicon substrate. This mirror was carefully cleaned<sup>2</sup> immediately before measurement. The deduced reflectance is  $0.9955 \pm 0.0008$ . This number compares well with 0.9952, a number deduced from manufacturer's reflectance traces made immediately after production. Thus the transmitting HF coatings appear to maintain their reflectance. At the time of testing, these coatings were over a year old.

In Fig. 3, data from a witness sample of a potential enhanced-gold coating, prepared by a commercial manufacturer for the HF laser ring resonator, are shown. A gold monolayer on a Zerodur flat substrate is overcoated by four layers of zinc sulfide and thorium fluoride. This surface is nontransmitting. With the use of the three-mirror CAPS cavity, the deduced reflectance is found to be  $0.9948 \pm 0.0008$  at the shallow incidence angle of  $6.6^\circ$ . At such a small incidence angle, the reflectance behavior at normal incidence is reasonably approximated.

Silver monolayers prepared in-house on Zerodur flats were also studied. A sample placed in a dry box two days after being coated, and left there for

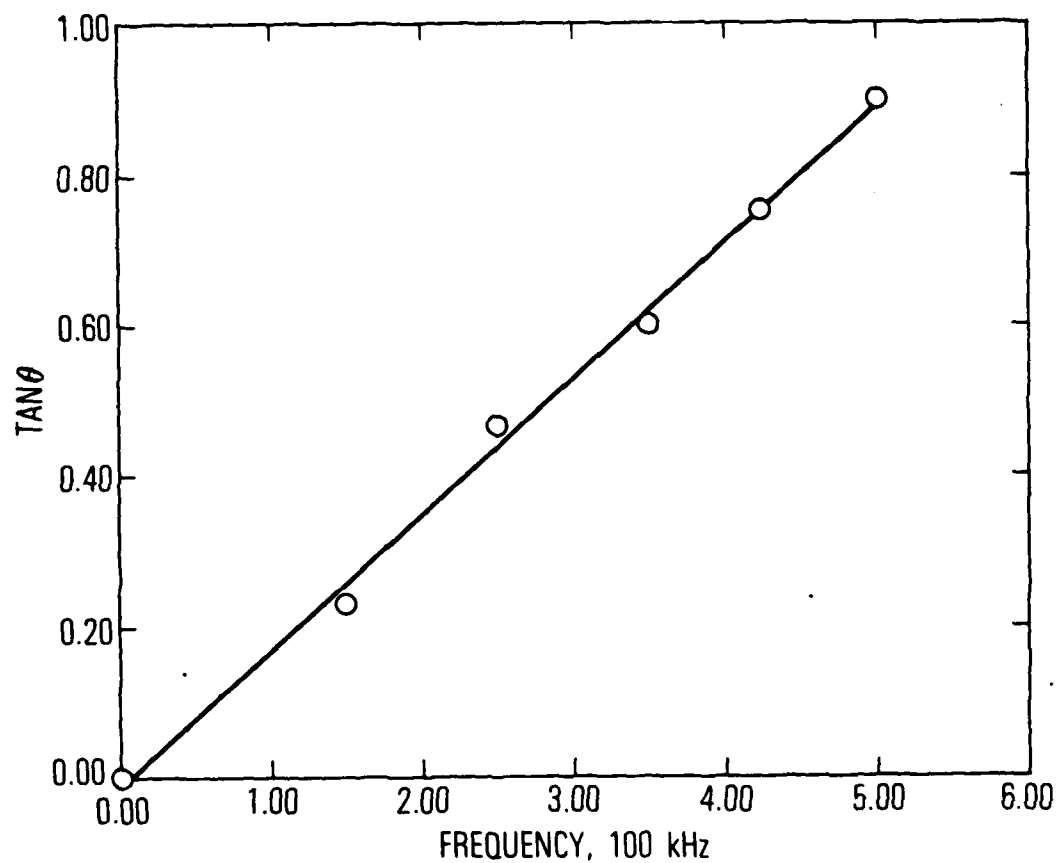


Fig. 3. Plot of  $\tan\theta$  vs. Modulation Frequency for Three-Mirror CAPS Cavity with Nontransmitting Sample. Sample is gold monolayer with four layers of ThF/ZnS on a Zerodur substrate. End mirrors as in Fig. 2. Test conditions as in Fig. 2. Measured reflectance  $R = 0.9948 \pm 0.0008$  at s-polarization,  $6.6^\circ$  incidence angle.

three weeks, was tested without cleaning. The reflectance measured was  $0.9903 \pm 0.0008$  at a  $7.1^\circ$  angle of incidence and a wavelength of  $2.911 \mu\text{m}$ . The sample was returned to the dry box after the test and withdrawn two days later to be cleaned.<sup>2</sup> Because the soft silver had no overcoat, some microscratching occurred, but measurements showed improvement in the reflectance to  $0.9926 \pm 0.0008$ . Thus some of the degradation in reflectance which is due to local atmospheres appears recoverable.

The best accuracies to date for a two-mirror cavity can be summarized in Fig. 4, where the uncertainty  $dR/R$  in the reflectance measurement  $R$  is plotted as a function of  $R$ . The curve was generated on the basis of an uncertainty of 20 ppm at 0.9998 reflectances on coatings for a wavelength of 874 nm (black dot). That uncertainty corresponded to phase-angle uncertainties of  $\pm 2^\circ$ . In the HF-wavelength regime,  $2.9 \mu\text{m}$ , the uncertainty in reflectance is found to be on the same straight line, again representing  $\pm 2^\circ$  uncertainties in phase angle. Figure 4 demonstrates that the inherent accuracy in the measurement of  $R$  depends on  $R$  in the CAPS method, and this aspect is one of the important positive features of the method.

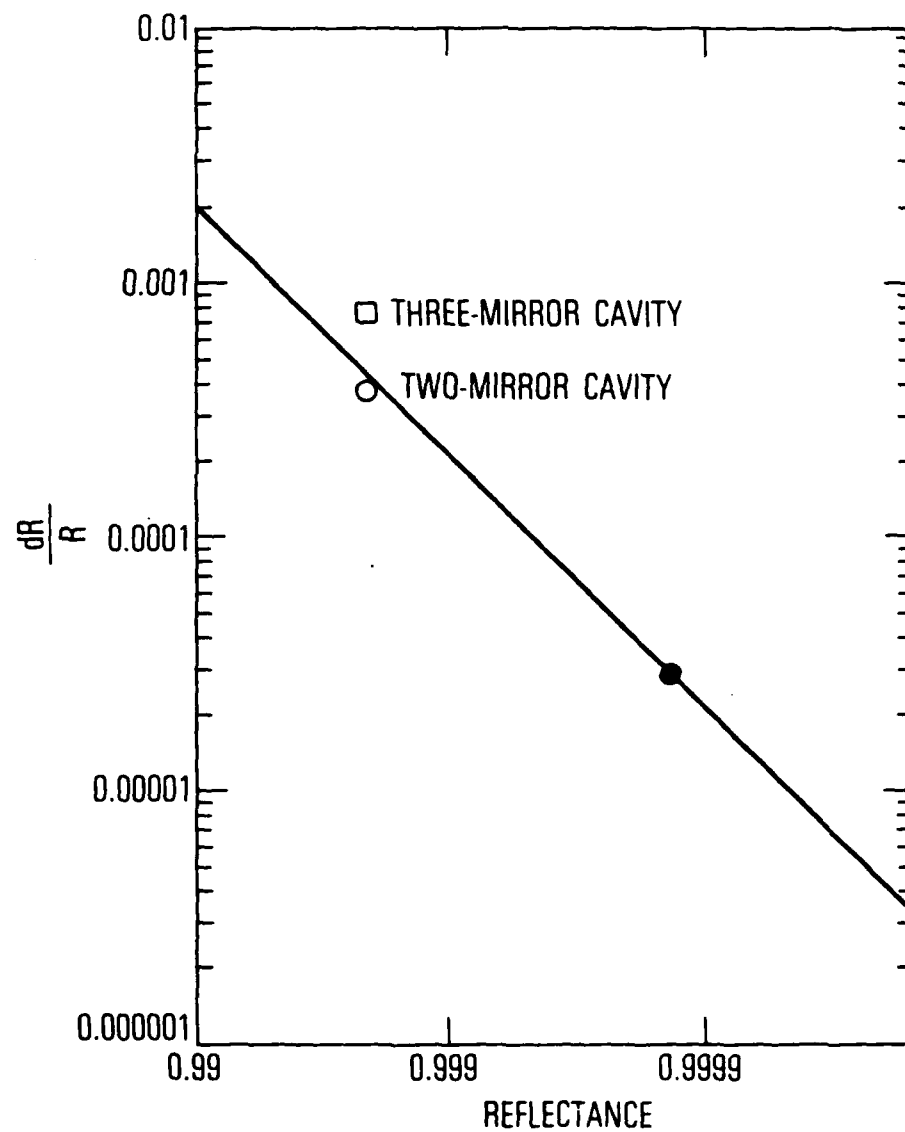


Fig. 4. The Accuracy of the Reflectance as Measured by CAPS as a Function of  $R$

#### IV. CONCLUSION

The accuracy and precision of the cavity phase-shift method have been markedly improved by the addition of the test cavity dither and by improved mode-matching techniques. Various types of three-mirror test cavities, which provide the capability of studying spherical optics with any type of substrate, have been provided. The method has been used to support the DARPA HF optical resonator research program of R. A. Chodsko in our laboratory.

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